Enhancing Sheared Edge Stretchability of AHSS/UHSS

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2017 DOE VTO ANNUAL MERIT REVIEW
JUNE 6, 2017

PROJECT ID# LM106

Overview

Timeline

- Project start date: FY15
- Project end date: FY17
- Percent complete: 70%

Budget

- DOE
  - $450K/YR (FY15-FY17)
- Industries (in-kind)
 - $300K/YR (FY15-FY17)

Barriers

- Edge stretchability is a key barrier for the increasing application of AHSS/UHSS.
- Edge stretchability is influenced by many factors including material microstructures, blank preparation processes, die wear, and edge loading conditions.
- Lack of a quantitative and predictive understanding linking microstructural characteristics to edge stretchability.

Partners

- Ford: C Chiriac, R Sohmshetty
- US Steel: B Hance, MF Shi
- AK Steel: KS Raghavan, YW Wang
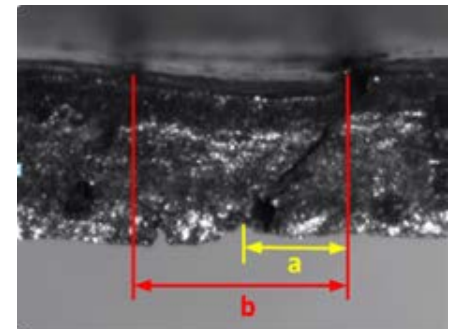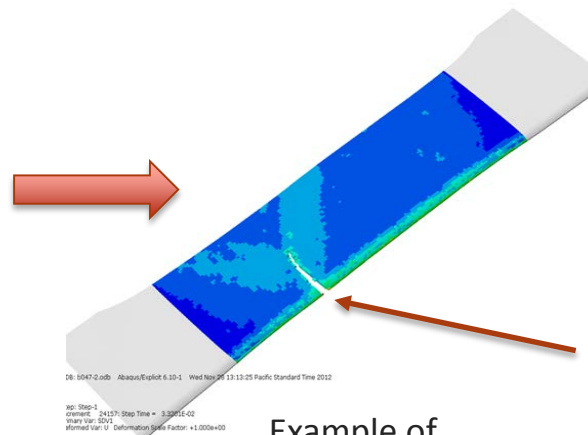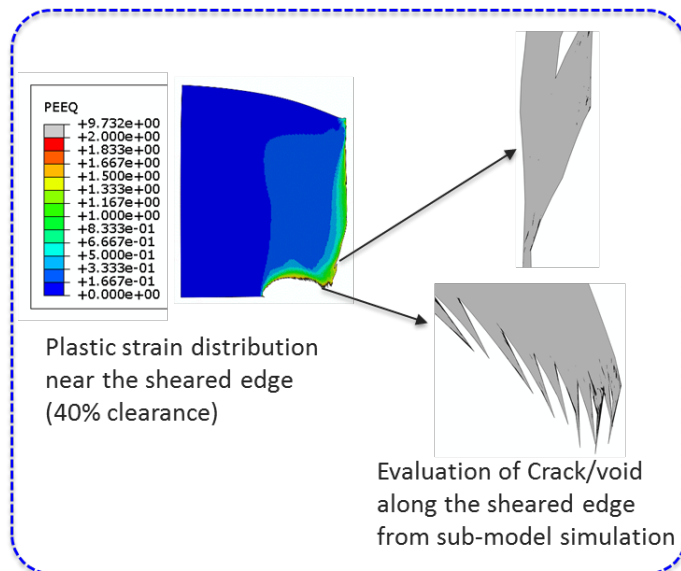- Oakland Univ: SF Golovashchenko

Relevance and Project Objectives

▶ Enhance the sheared edge stretchability of AHSS/UHSS by

■ Obtaining fundamental understanding on the role of microstructure on sheared edge stretchability

■ Building predictive capabilities to quantify relationships between microstructures and trimmed edge quality including subsequent stretchability

▶ Accelerate the development of next generation AHSS (steel companies) and enable a rapid and cost-effective deployment of AHSS/UHSS in vehicle structures (auto OEMs) for substantial mass savings that meet the lightweighting goals specified in the VTO MYPP
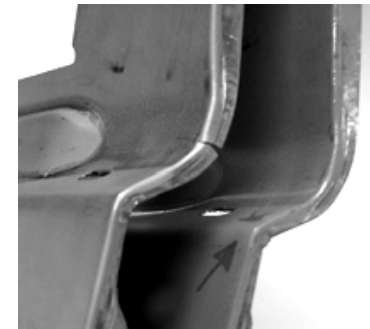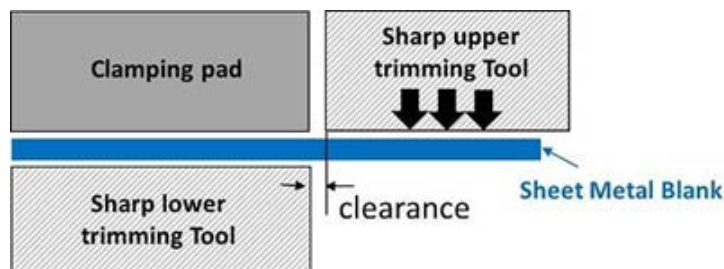
Examples of edge fractures in AHSS stamped parts

Technical Approaches

- ► Task 1. Literature review on DP980 hardening behaviors
- ► Task 2. Material collection and macro-/micro- material property characterization
- ► Task 3. Macro Trimming/Piercing simulations and experiments
- ► Task 4. Micro damage characterization/prediction at SAZ
- ► Task 5. Macro fracture/stretchability/HER prediction and experiments
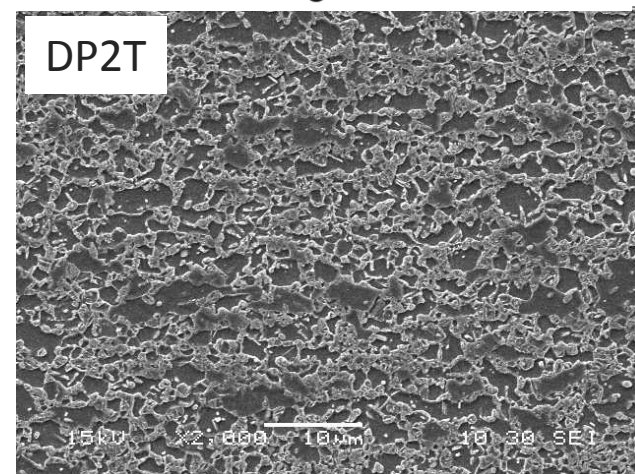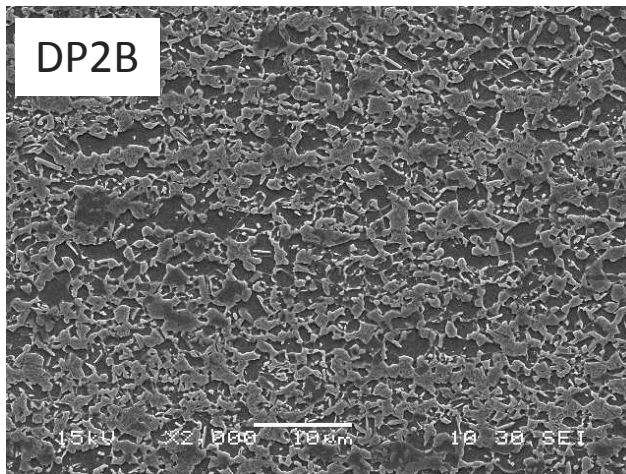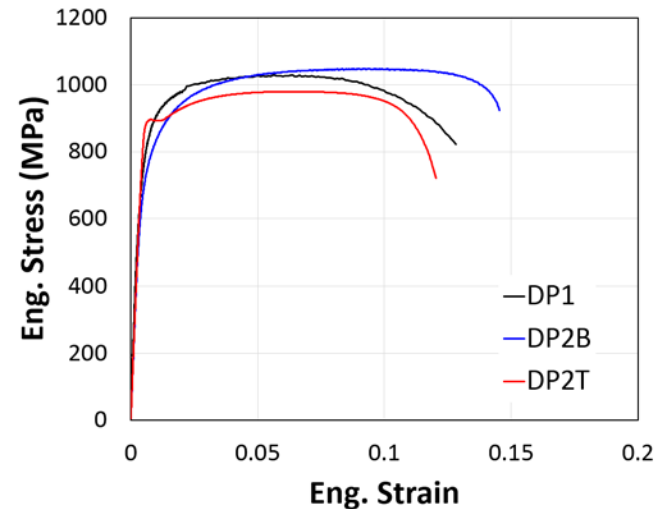- ► Task 6. Optimizing process parameters and microstructures for trimmed edge stretchability
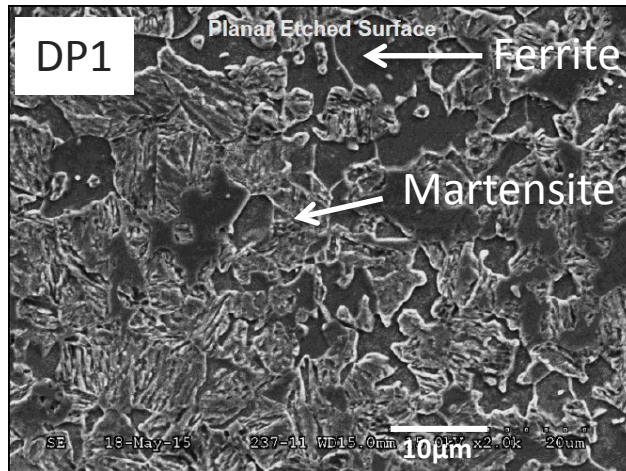

Plastic strain distribution near the sheared edge (40% clearance)

Evaluation of Crack/void along the sheared edge from sub-model simulation

Example of stretchability simulation

Milestones and Go/No-go Decision Points

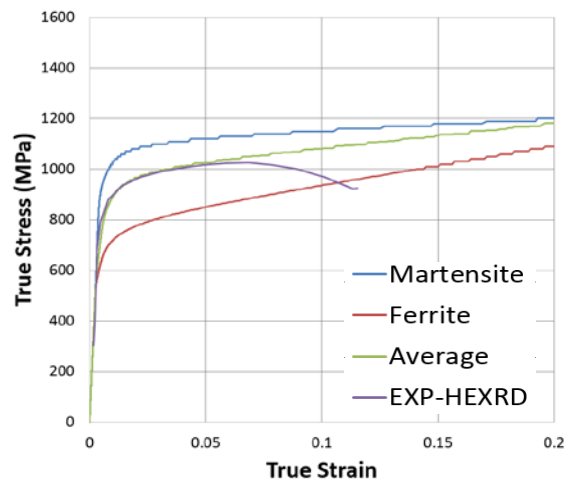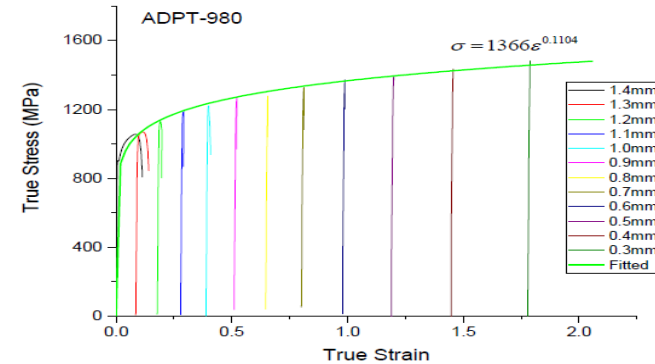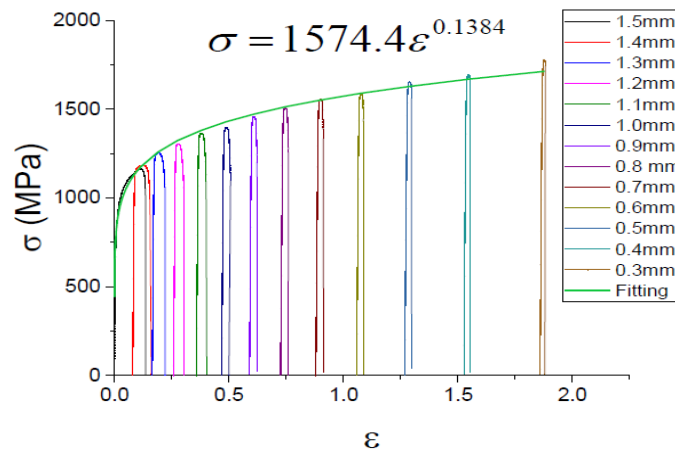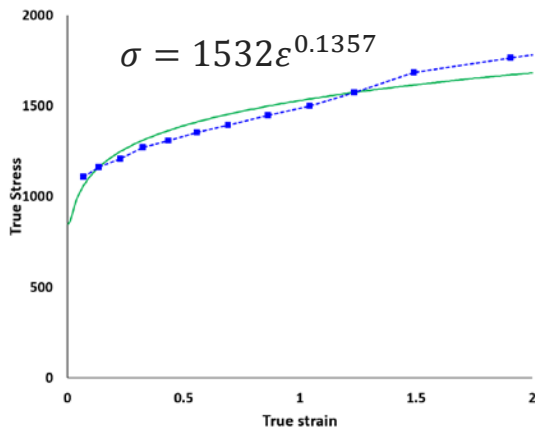| Date	Milestone or Go/No-go	Goal description	Status
12/31/2014	Milestone	Acquire materials and complete literature review on different DP980 hardening behaviors	Complete
3/31/2015	Milestone	Complete experimental characterizations of micro- and macro-scopic properties of DP980	Complete
6/30/2015	Milestone	Complete shearing/piercing experiments on two DP980 steels with different clearances	Complete
9/30/2015	Milestone	Complete macroscopic shearing/piercing process simulation with experimental validation	Complete on 12/31/2015
3/31/2016	Go/No-go	Predicted burr geometry >90% accurate for different DP980 under different clearances	Complete
3/31/2017	Milestone	An experimentally validated numerical method to predict edge damages in AHSS/UHSS sheet steels during shearing processes	Complete
6/30/2018	Milestone	Optimized cutting parameters for the optimal sheared edge stretchability of DP980 grades with different microstructures	On Track

Microstructure Characterization (AK/USS)

- ▶ Three DP980 steels : DP1, DP2B, DP2T (B: Base material; T: Tempered)
- ▶ Grain size (DP1) > Grain size (DP2B and DP2T)
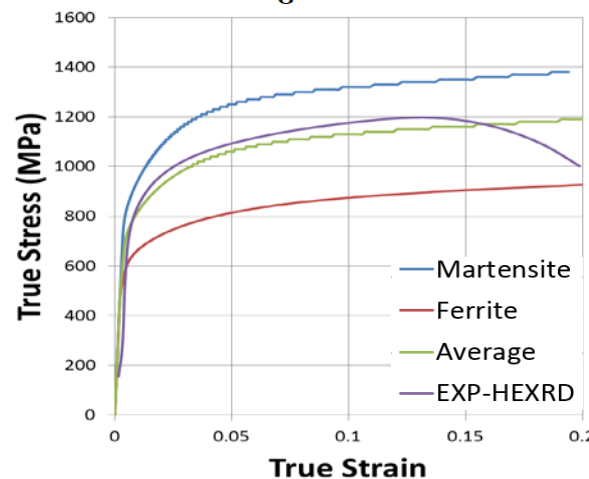- ▶ Flow stress decreases after tempering (DP2B vs. DP2T)
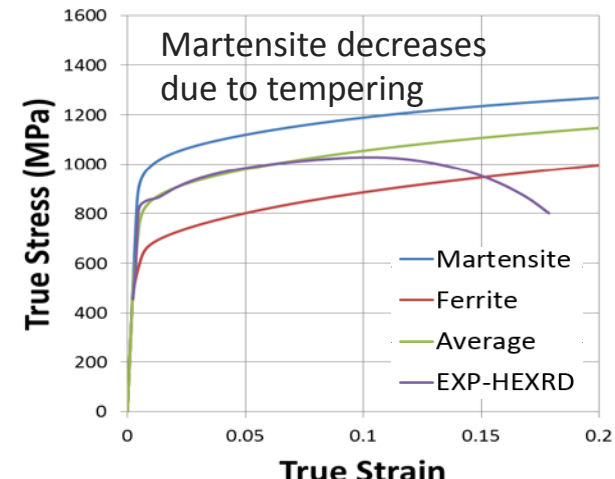
Material Property Characterization (PNNL/AK/USS/OU)

▶ Accumulated rolling and tension tests → Flow behavior at large strains

▶ In-situ HEXRD tensile test → Ferrite and martensite phase properties*

$$\sigma = 1532\varepsilon^{0.1357}$$

$$\sigma = 1574.4\varepsilon^{0.1384}$$

ADPT-980

$$\sigma = 1366\varepsilon^{0.1104}$$

Martensite decreases due to tempering

DP1

DP2B

DP2T

*Hu, X. et al., MMTA 47, pp.5733-5749, 2016.

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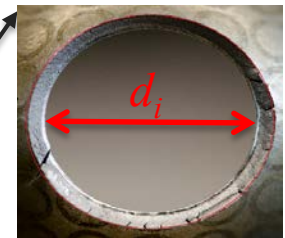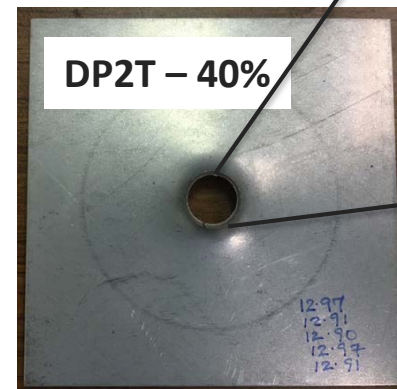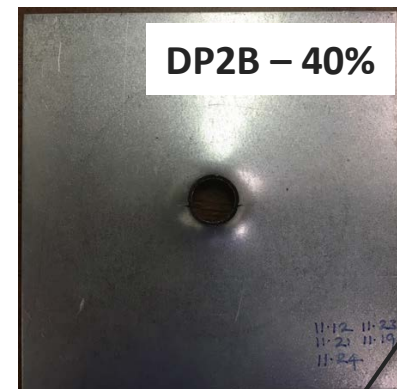NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

► Tempered DP steel : ~100% higher HER (Hole Extrusion Ratio)

► Changed phase properties have effects on HER

► Highest HER around ~20% clearance (No burr observed)

Schematics

DP2B − 40%

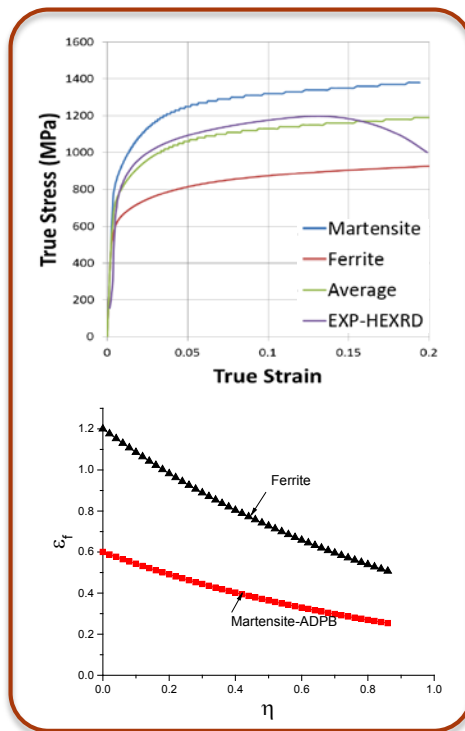DP2T − 40%
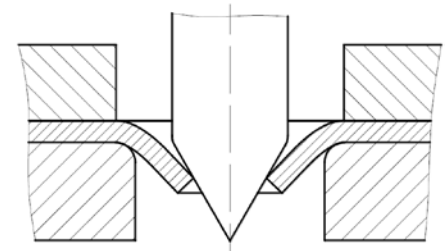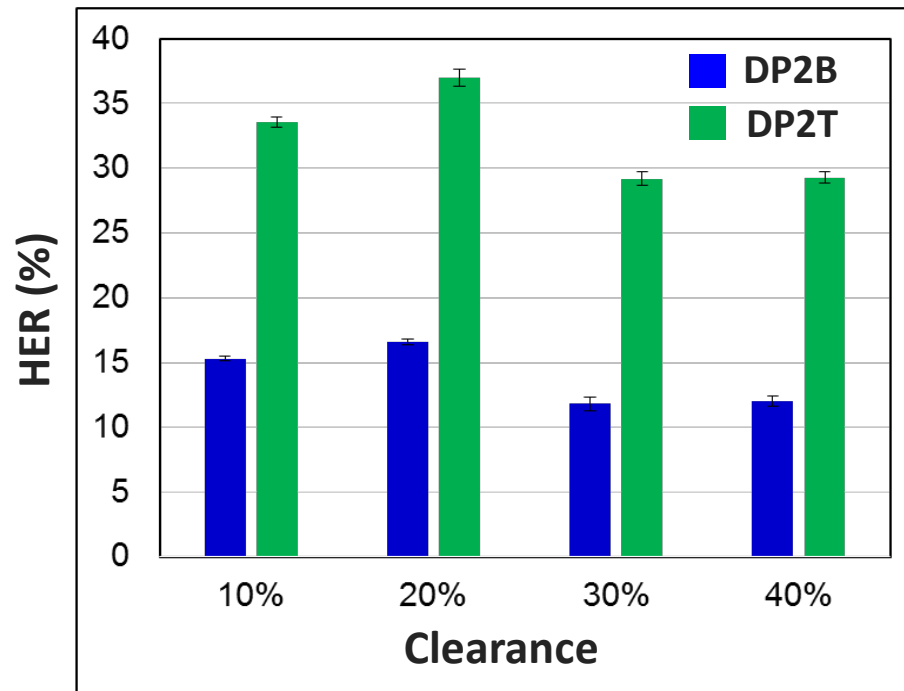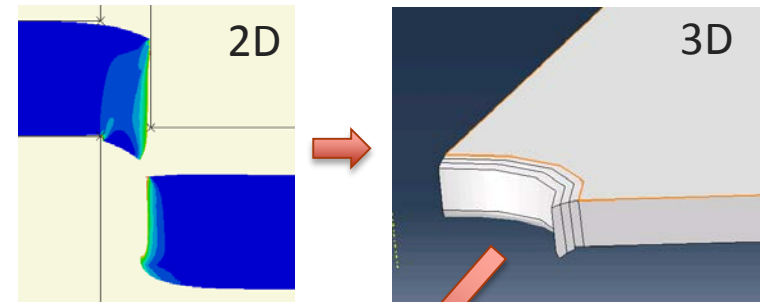
$$HER = \frac{d_i - d_0}{d_0} \times 100\%$$

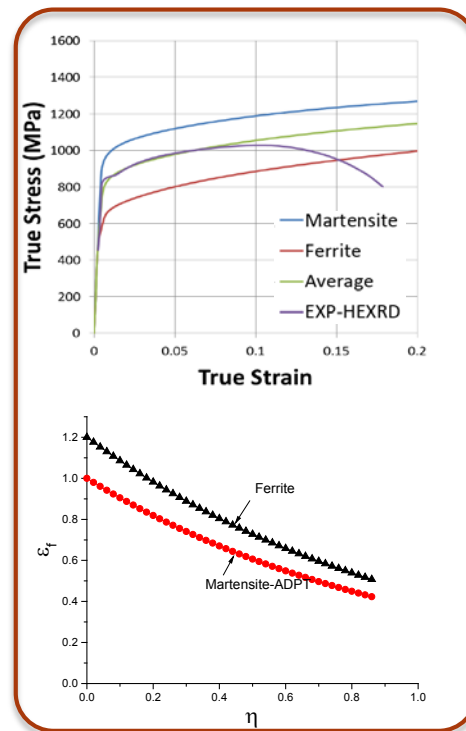d_i : inner Dia. after cracking
d_0 : initial Dia.

Measurement of HER

Hole extrusion ratio

*Raghavan, K.S. et al., Linking constituent phase properties to edge stretchability in DP980 steel, presented in MS&T16, Oct. 23-17, 2016, Salt Lake City, Utah, USA.

Hole Extrusion Simulations (PNNL) (Effects of Tempering)

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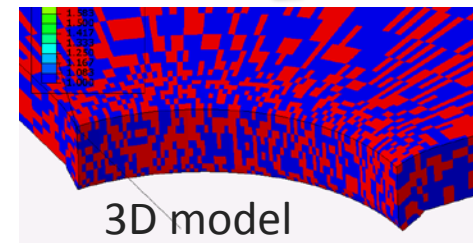NATIONAL LABORATORY
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▶ 2D mapping to 3D : geometry and field variables

▶ Incorporated HEXRD-measure phase properties, volume fraction, textures and material heterogeneity
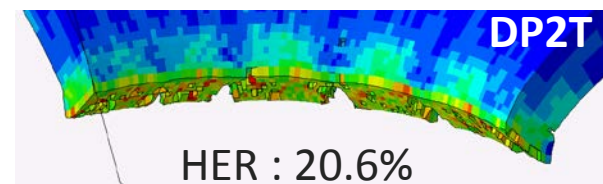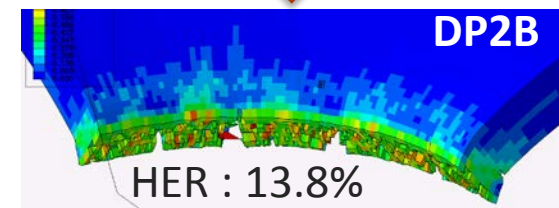
▶ Johnson-Cook damage model

2D

3D

ferrite
martensite

3D model

DP2B

HER : 13.8%

DP2T

HER : 20.6%

DP2B

DP2T

DP2B

44 % Clearance
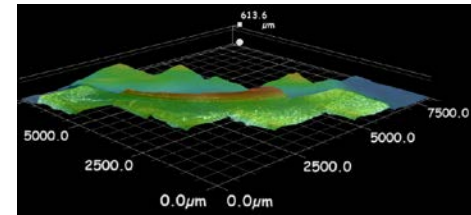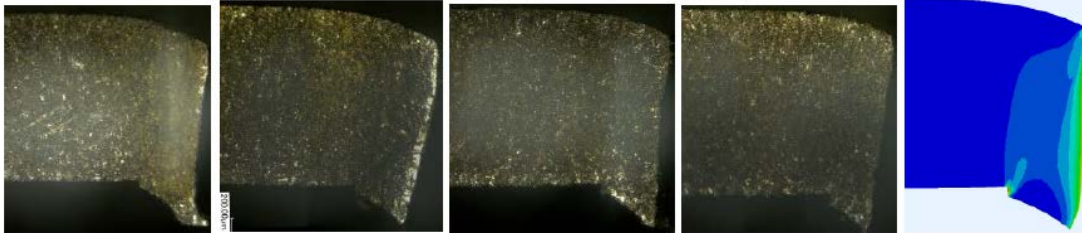
30 % Clearance

20 % Clearance

10 % Clearance

3D image of burr
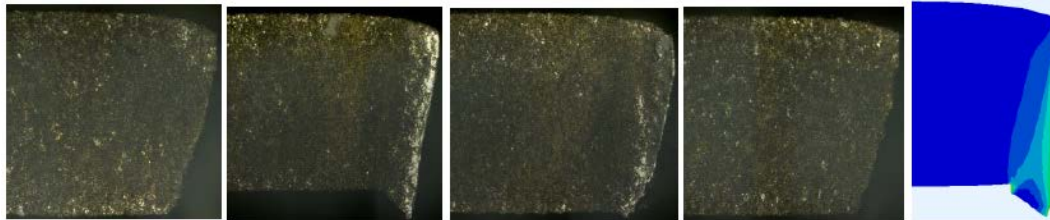
- ▶ 2D axisymmetric model
- ▶ Fracture strain curves from trimming simulation
- ▶ Predicted burr at higher clearances (i.e., 30, 40%)
- ▶ Cannot predict the edge variation

Burr Height Variation in Hole Piercing (PNNL)

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▶ 3D hole piercing simulation with different punch positions
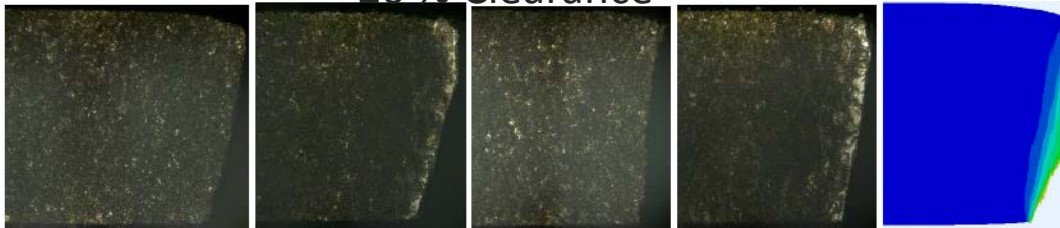
▶ Die-punch misalignment may induce different clearance along the circumference leading to burr height variation

DP2B

No burr

Burr height (µm)

30% clearance

Burr height (µm)

40% clearance

Punch

Clamping

Blanking material
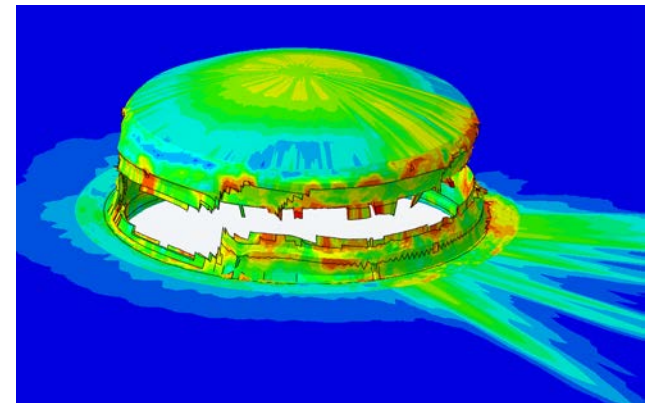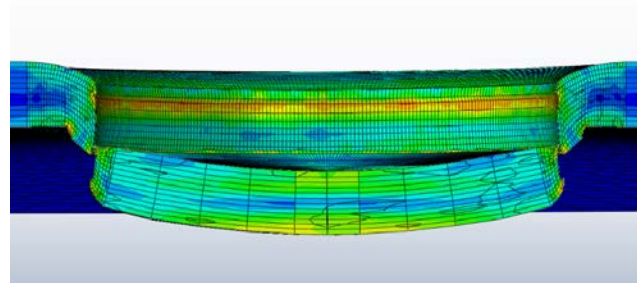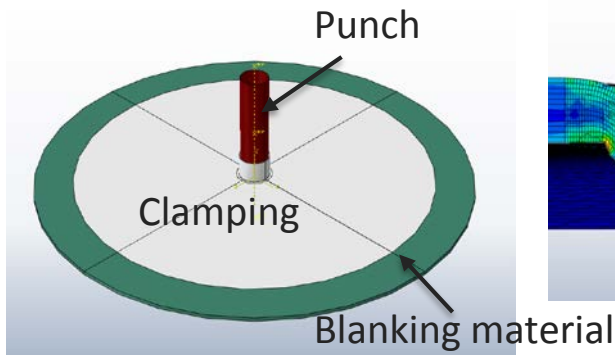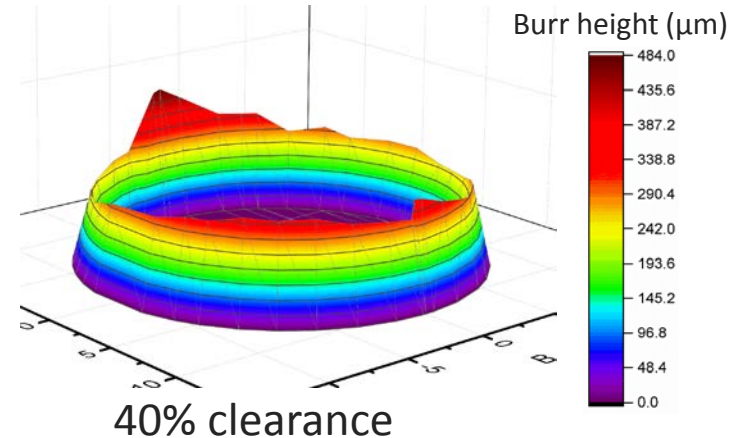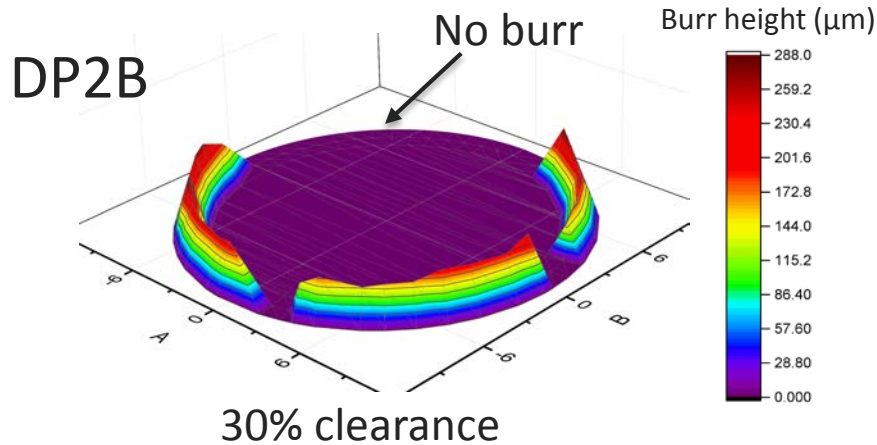
3D hole piercing simulation

40% clearance with accurate punch position

30% clearance with off-center punch position (50µm)

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High resolution
video camera

Sheared
sample

Digital
extensometer
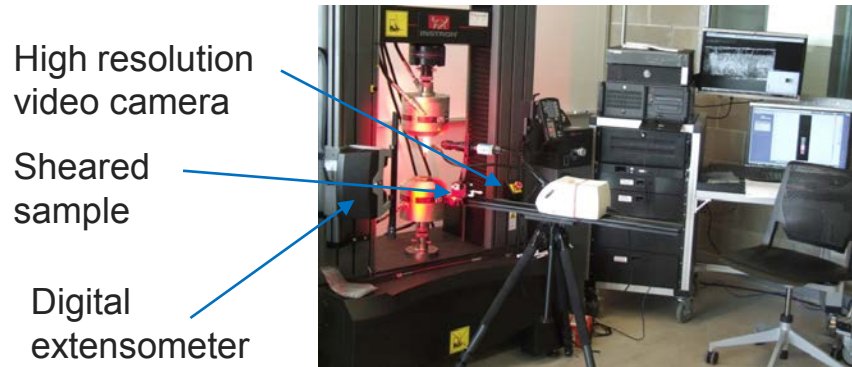
► Sheared edge is gridded with 1mm square grid to track the specific locations of fracture initiation

► DP1 is under testing/analysis
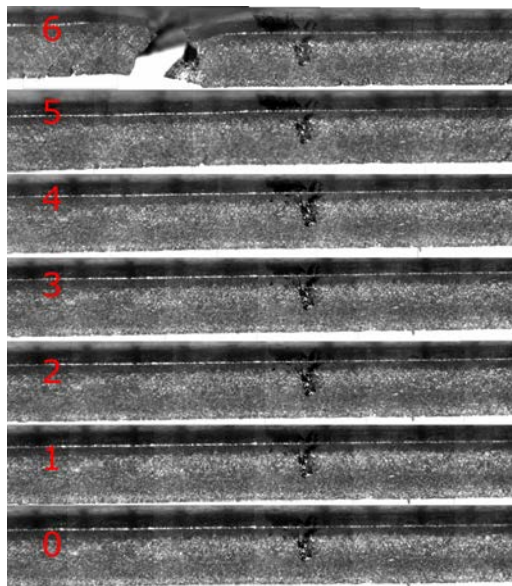
Evolution of the sheared edge during stretching test
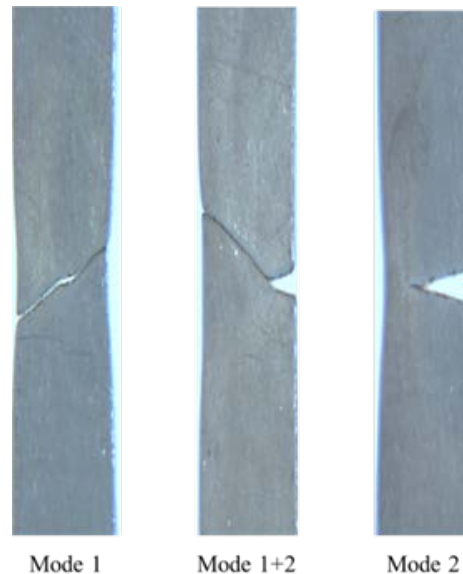
In-plane failure mode during stretching test

Mode 1   Mode 1+2   Mode 2
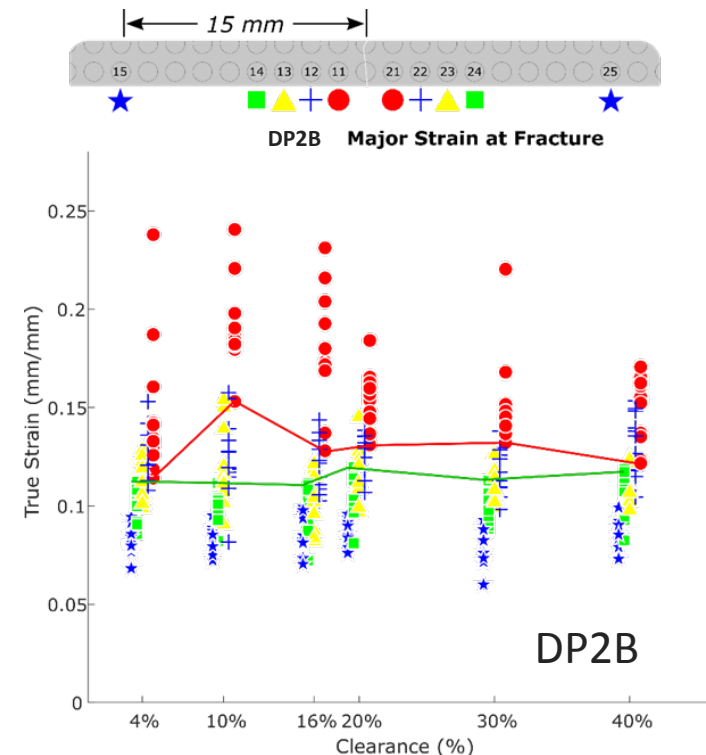
Effects of clearance on fracture strain

DP2B   Major Strain at Fracture

DP2B

DP2B

DP1
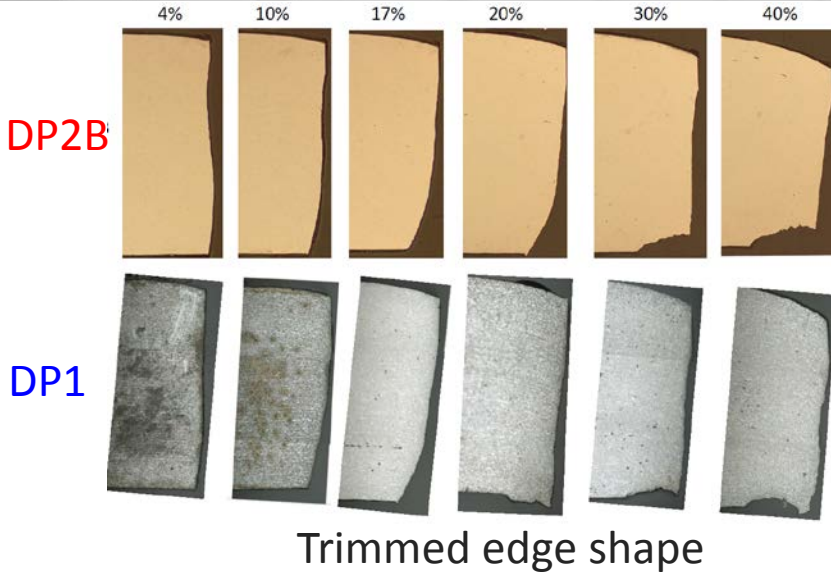
Trimmed edge shape

▶ 2D plane strain model ($10 \times 6\mu m^2$ mesh)

▶ Macro fracture strain curve from comparing trimmed edge shapes between experiment and simulation

▶ John-Cook damage model for macro fracture :

$$\varepsilon^f = a_0 + a_1 e^{-b\eta}$$

DP2B

DP1

Simulation results

Input s-e curves

$a_0=1.04$
$a_1=0.5$
$b=0.12$

$a_0=0.97$
$a_1=0.5$
$b=0.12$
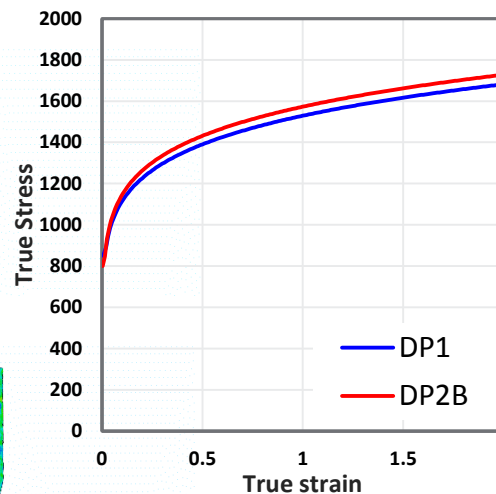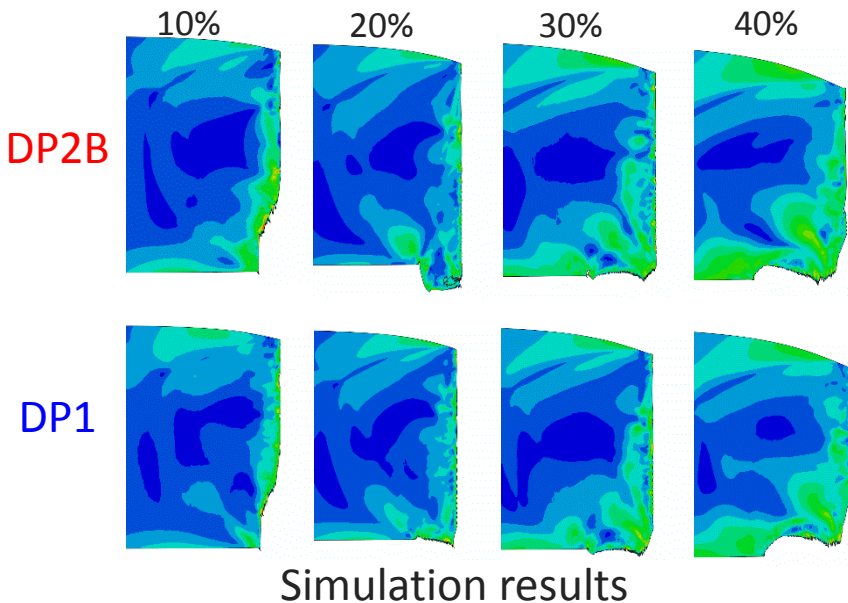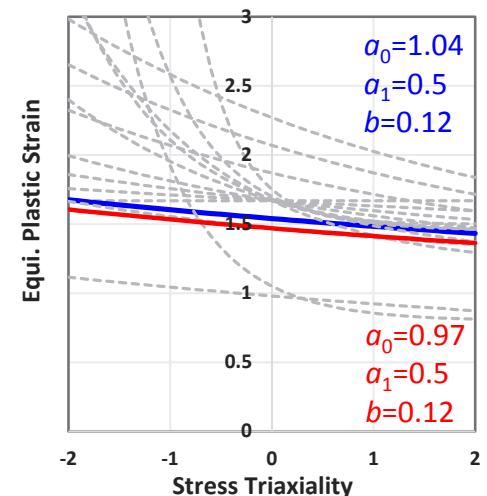
Fracture strain [13]

*Cheng, G. et al., Investigation on the fracture behaviors in trimming process for DP980, to be submitted for journal publication , 2017.

▶ Adopted porosity-based Gurson model to consider trimming-induced cracking

▶ Considered combination of strain-based and porosity-based damage accumulation

40% clearance

Peeq

Void distribution from submodeling

PEEQ mapping

Void mapping
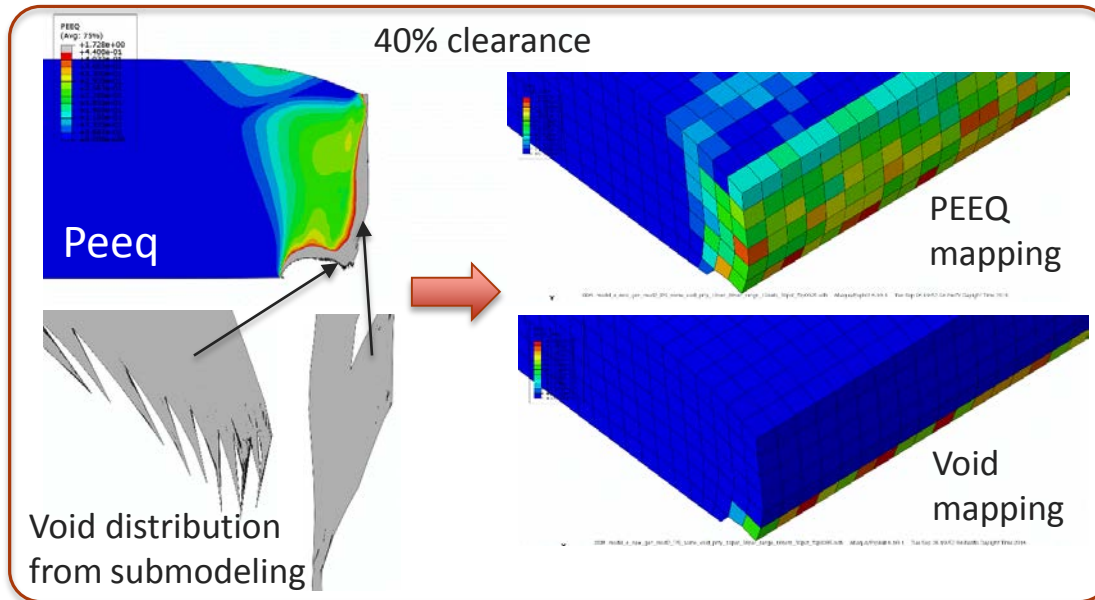
$$D = \int_0^{\varepsilon_p} \frac{d\varepsilon_p}{\bar{\varepsilon}_f(\eta)} + \int_0^{f_{gr}} \frac{df_{gr}}{f_{gr,f}(\eta)} = 1$$

Split failure mode

$$\varepsilon^f = 0.408 + 0.2e^{-0.12\eta}$$

$$\varepsilon^f = 0.351 + 0.15e^{-0.12\eta}$$

RVE size effects on fracture strain*

J-C fracture strain curves

Critical void growth

Effects of damage on s-e curves
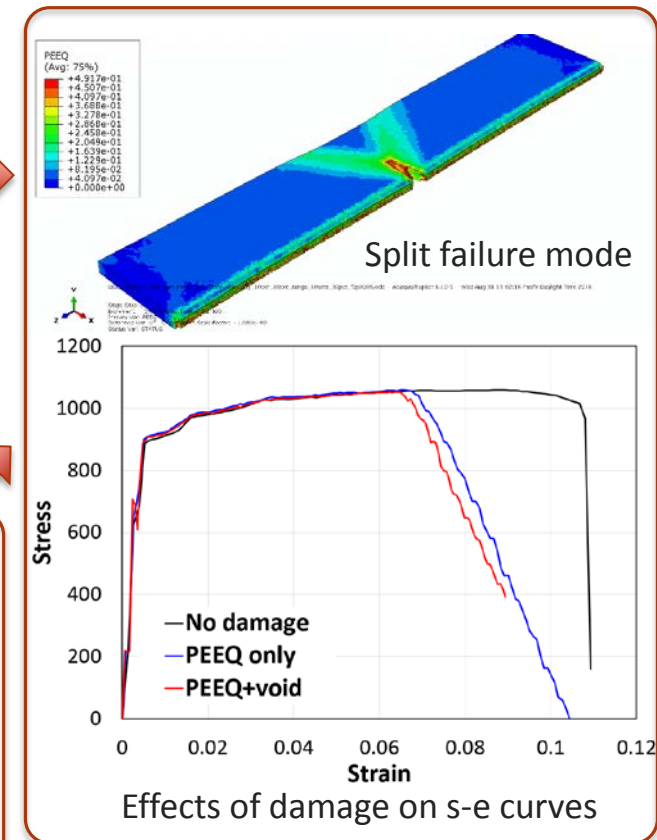
*Cheng, G. et al., Predicting size-dependent fracture strains of DP980 with a microstructure-based post-necking model, submitted to Int. J. Fract. 2017.

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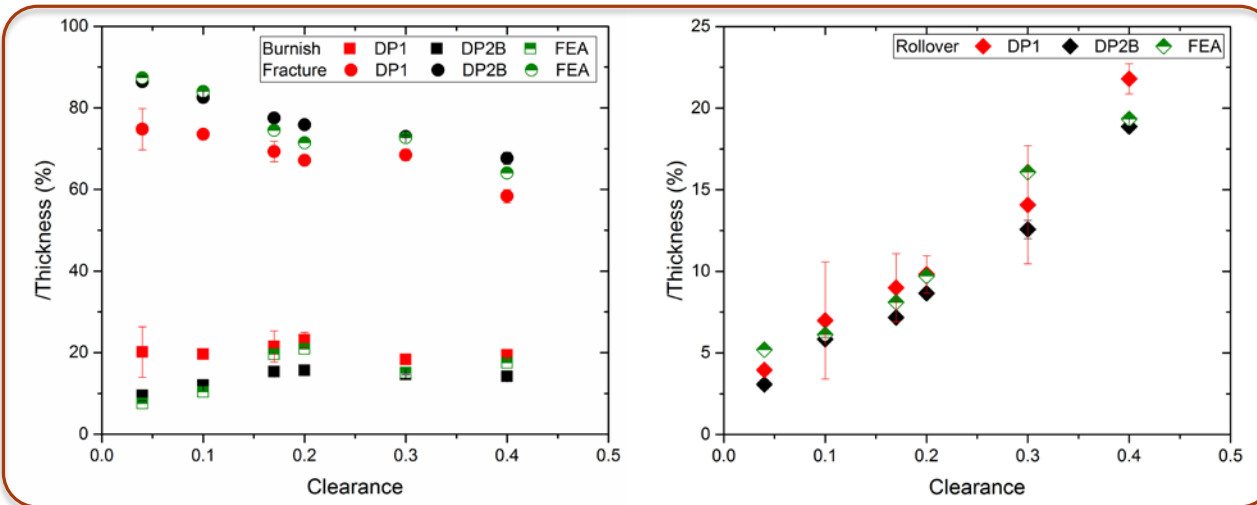
Trimming

► Predicted edge shape parameters agree well with the experiment

Hole piercing

Microscopic Damage Characterization of SAZ (PNNL)

▶ Average of $\bar{\varepsilon}_f$ for ferrite is ~1.5 : Similar to the fracture strain level obtained from trimming simulations

▶ Observed more and larger internal cracking in DP2B

$$r = \frac{width}{length} \qquad \bar{\varepsilon}_f = \frac{1}{\sqrt{3}}\ln(r)$$

Ferrite grain deformation (40%)

DP1 (40%)

DP2B (40%)

Possible internal cracking from shearing
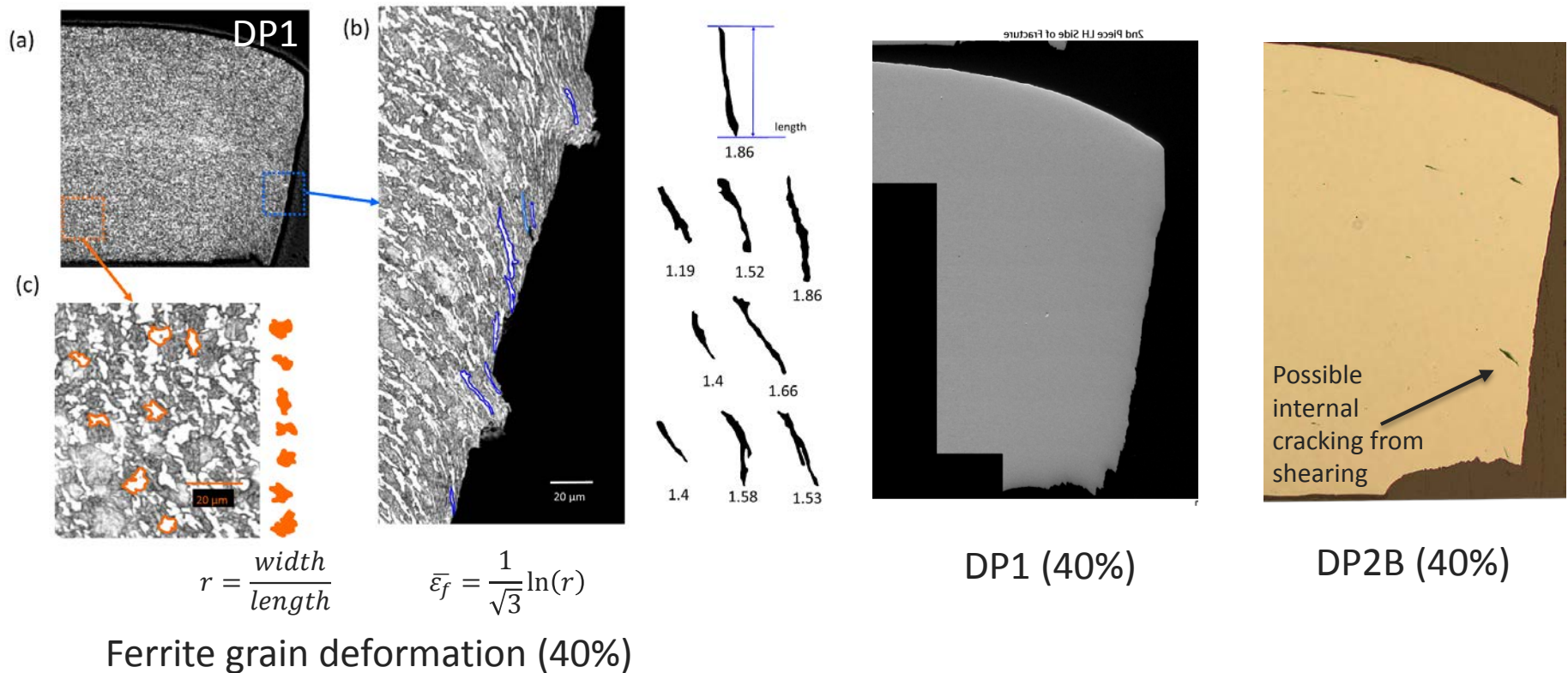
Responses to Previous Year Reviewers' Comments

▶ **Approach to performing the work:**

- This reviewer commented that the project will study the edge stretchability of advanced high-strength steels (AHSS)/ ultra-high-strength steels (UHSS) to increase application of AHSS/UHSS into vehicle structures for weight reduction and crash performance. The reviewer was pleased to see some numerical and physics studies other than experimental testing and characterization. The link between the material microstructure and edge stretchability is critical to guide the design and development of future generation of AHSS/UHSS

- Response: We have been working on three different DP980 steels whose microstructures and phase properties are different. In our computational scheme, their microstructures and phase properties are explicitly considered within the micro-scale models. It is therefore expected that our modeling method can provide the fundamental understanding on the effects of various microstructural features on the stretchability as well as a design guideline for future generation of AHSS

▶ **Technical accomplishments and progress toward overall project and DOE goals:**

- The reviewer said that constitutive equations are sound and directionally correct, and that the project needs to deliver process models as part of the deliverables. The reviewer anticipates these results will be provided based on the strength of the team.

- Response : The numerical models and methods developed during the project will be the part of deliverables. The associated technology will be transferred to automotive and steel industries. Our findings will also be presented and published in the conferences or other engineering journals.

Collaborations

▶ Experimental materials characterizations at micro- and macro-scales (AK, USS, OU, PNNL)

▶ Experimentally trimming task with die wear (Ford+OU)

▶ Phase property and SAZ characterizations (PNNL+APS)

▶ Experimentally obtain quantitative relationship between edge stretchability and edge quality indicators:

■ Straight edge (Ford+OU)

■ Hole punch (AK+USS)

▶ Develop predictive modeling capability linking microstructures to trimming conditions to edge stretchability (PNNL)

▶ Develop optimized microstructure and process parameters based on ability of sheared surface to stretch (PNNL+ AK + USS + Ford).

Remaining Challenges and Barriers with Future Work

- ▶ Task 5. Macro fracture/stretchability/HER prediction and experiments
  - ▶ Experimental validation is underway with the developed computational scheme
  - ▶ 2D axisymmetric model cannot predict the edge variation along hole circumference
    - ▶ 3D one-stroke model (i.e., hole piercing/extrusion simulation) with off-center punch can be used to consider the edge variation effects
    - ▶ *Piercing-induced void is difficult to be mapped near the edges of 3D one-stroke model*
- ▶ Task 6. Optimizing process parameters and microstructures for trimmed edge stretchability

Preliminary one-stroke simulation

Punch tool

45°

Blanking materials
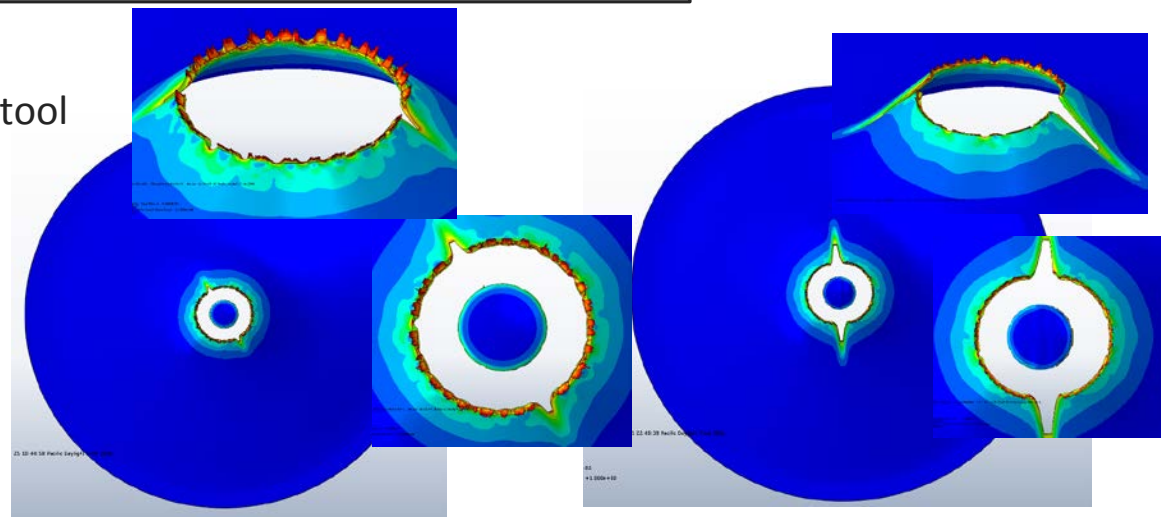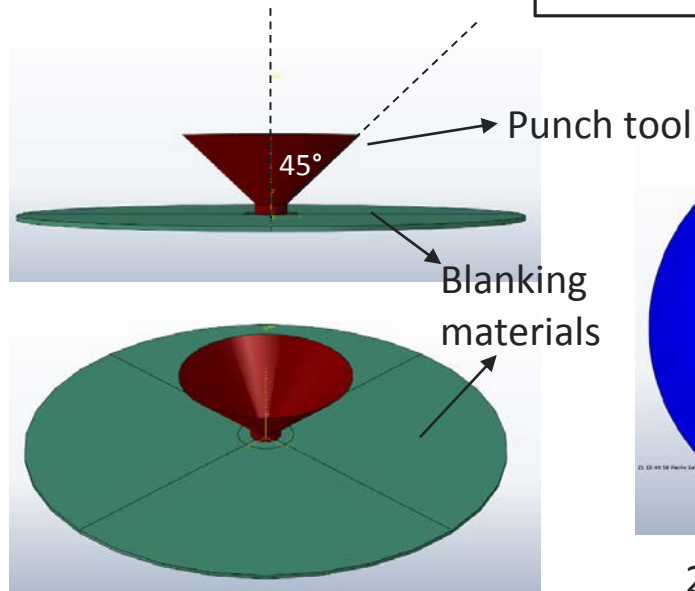
20% clearance at center

20% clearance at off-center

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Summary

- ▶ Task 2: Material property characterization
  - ■ *Completed the material characterization for three different DP980 steels*
- ▶ Task3: Trimming/Piercing simulation and experiment
  - ■ *Completed the trimming/piercing for different clearances with the corresponding simulations*
  - ■ *Performed edge characterization after cross-sectioning*
  - ■ *Predicted edge geometry with good accuracy for trimming/piercing*
  - ■ *Examined the off-center punch effects on the pierced hole*
- ▶ Task 4: Microstructural damage characterization at SAZ
  - ■ *Measured grain deformation and identified internal cracking near SAZ*
- ▶ Task 5: Macroscopic fracture/stretchability prediction and experiments
  - ■ *Performed stretchability and hole extrusion tests for different clearances*
  - ■ *Developed the computational method to predict the stretchability*